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Economics of Rare Earths: the Balance Problem

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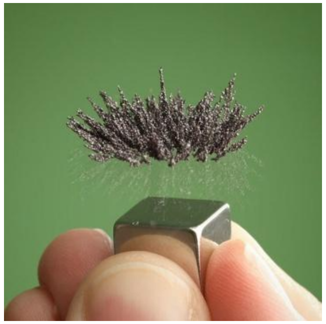
Early applications: mixed rare earths

- Mainly lanthanum and cerium
- **Catalyst industry**
  - Stabilization of zeolites for fluid cracking catalysts (FCC) during steam regeneration
- **Metallurgy (mischmetall)**
  - Graphite nodularization in cast iron
  - Ultimate desulfurization of steels
  - Lighter flints made of iron-mischmetall alloy
  - Grain growth inhibition in light metals
  - Battery alloys (NiMH)
- **Glass industry**
  - Polishing powder (CeO_2)

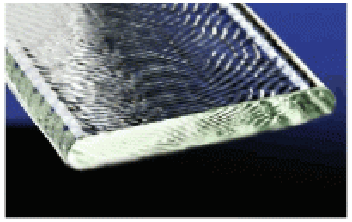
Modern applications: pure rare earths

- **Permanent magnets**
  - NdFeB (Nd,Pr,Dy)
  - SmCo (Sm)   (< 2% of market)



- **Phosphors**
  - Phosphors for trichromatic fluorescent lamps (Y, Eu, Tb, La, Ce)
  - Phosphors for CRTs (color television, computer monitors (Eu,Y)
  - X-ray intensifying screens (Gd,La,Tb)

- **Glass industry**
  - Optical glass (La)



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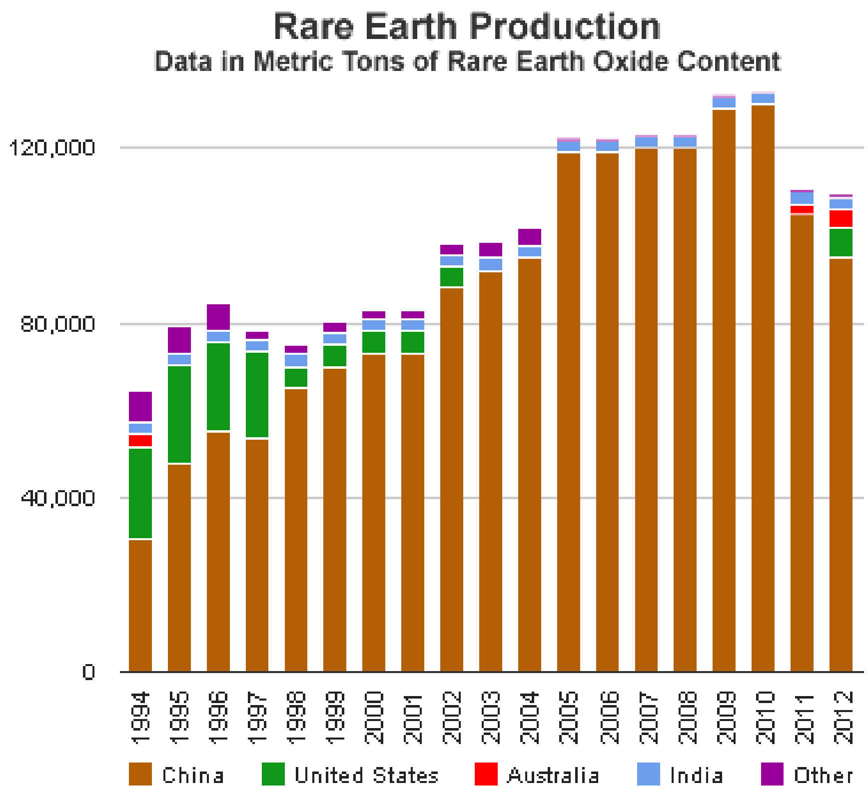
REE usage by application

Application	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Y	Other
Magnets			23.4	69.4			2	0.2	5		
Battery alloys	50	33.4	3.3	10	3.3						
Metallurgy	26	52	5.5	16.5							
Auto catalysts	5	90	2	3							
FCC	90	10									
Polishing powder	31.5	65	3.5								
Glass additives	24	66	1	3						2	4
Phosphors	8.5	11				4.9	1.8	4.6		69.2	
Ceramics	17	12	6	12						53	
Others	19	39	4	15	2		1			19	

(source: Lynas Corporation)[8]

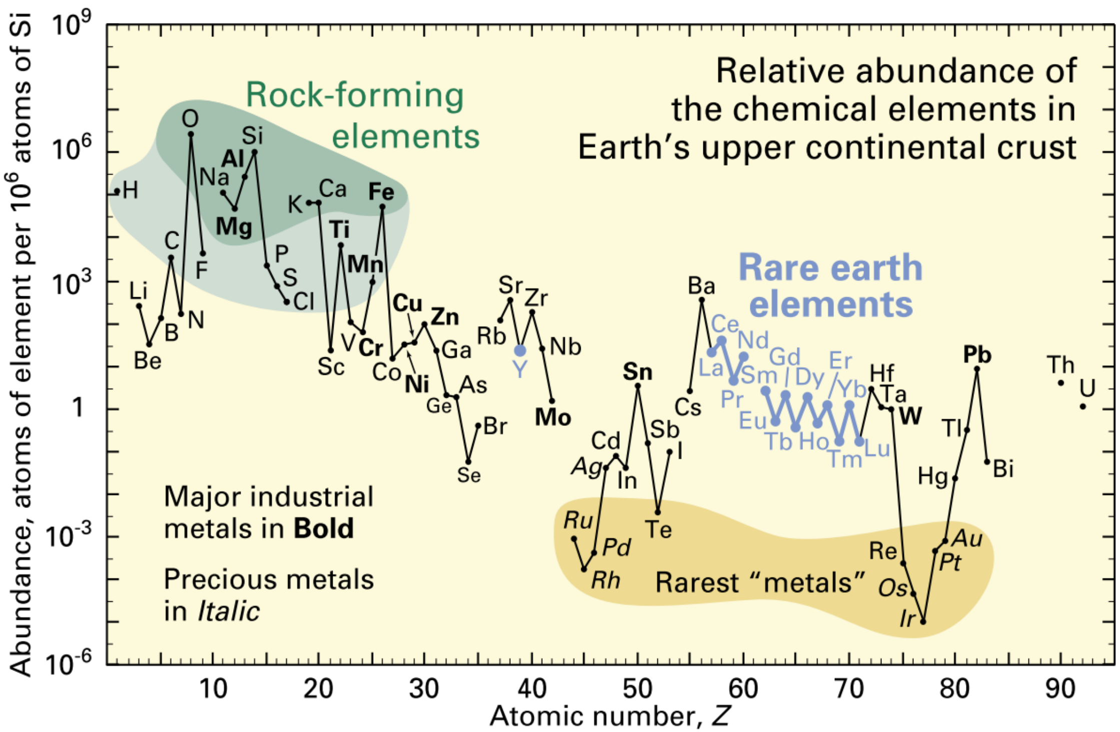
Global production of rare-earth oxides



REO production numbers do not reflect availability of individual REEs

Source: www.geology.com

Relative abundance of rare earths



- Elements become scarcer with increasing atomic number *Z* (abundances decrease over the lanthanide series)
- Elements with an even *Z* are more abundant than elements with odd Z (*Oddo-Harkins rule*)

Source: US Geological Survey

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REE content of selected minerals (%)

REE	Bastnasite Mountain Pass, USA	Bastnasite Bayan Obo, China	Monazite Mt. Weld, Australia	Xenotime Lehat, Malaysia	High Y RE laterite Longnan, China	Low Y RE laterite Xunwu, China	Loparite Kola Peninsula Russia
La	33.8	23.0	25.5	1.2	1.8	43.4	25.0
Ce	49.6	50.0	46.7	3.1	0.4	2.4	50.5
Pr	4.1	6.2	5.3	0.5	0.7	9.0	5.0
Nd	11.2	18.5	18.5	1.6	3.0	31.7	15.0
Sm	0.9	0.8	2.3	1.1	2.8	3.9	0.7
Eu	0.1	0.2	0.4	Trace	0.1	0.5	0.1
Gd	0.2	0.7	<0.1	3.5	6.9	3.0	0.6
Tb	0.01	0.1	<0.1	0.9	1.3	Trace	Trace
Dy	0.03	0.1	0.1	8.3	6.7	Trace	0.6
Ho	0.01	Trace	Trace	2.0	1.6	Trace	0.7
Er	0.01	Trace	Trace	6.4	4.9	Trace	0.8
Tm	0.01	Trace	---	1.1	0.7	Trace	0.1
Yb	0.01	Trace	---	6.8	2.5	0.3	0.2
Lu	Trace	Trace	---	1.0	0.4	0.1	0.2
Y	0.1	Trace	<0.1	61.0	65.0	8.0	1.3

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Consequences of REE abundances

- To get 1 ton of Eu_2O_3 from bastnäsite, one needs to produce (and sell) the following amounts of REOs (tons):

La_2O_3	300
CeO_2	450
Pr_6O_{11}	38
Nd_2O_3	118
Sm_2O_3	7.3
Gd_2O_3	1.4
Y_2O_3	0.9

Ref.: P. Falconnet, Basic and Applied Aspects of Rare Earths, 1989 (Venice –Italy) p. 27

Balance problem

- **Balance problem** = demand and supply of the individual rare-earth elements (REEs) have to be equal at any time
- Became an issue when applications shifted from the use of mixed rare earths to pure rare earths
- Important for REE manufacturers
- Concept introduced by P. Falconnet (Rhône-Poulenc) *J. Less-Common Metals* 111 (1985) 9.

K. Binnemans et al. *JOM* **65**, 846-848 *(*2013).

Balance problem

- Ideal situation: perfect balance between demand and production of all REE elements
- Market in balance corresponds to lowest price for any REE: production costs are shared by all elements
- Market in balance is very difficult to obtain, because of changes in demand by changes in applications
- Compromise between two alternatives:
  - Adjusting overall production to optimize production costs: creates surpluses of some REEs and shortages of other REEs (increases price of elements high in demand)
  - Increasing overall production to meet demand of all REEs and stockpiling other REEs (increases overall price)

Ref: P. Falconnet, J. Less-Common Met. 111 (1985) 9.

Neodymium-driven LREE market

- Present light REE market is driven by demand for Nd for NdFeB magnets (about 25,000 tons in 2011)
- Sufficient quantities of REE ores have to be mined to produce at least 25,000 tons of Nd
- Excess of La, Ce, Sm

Dysprosium-driven HREE market

- Balance problem is less a problem for HREE market (much smaller volumes than LREE)
- Present heavy REE market is driven by demand for Dy for NdFeB magnets (about 1,600 tons in 2011)
- Excess of Gd, Ho, Tm, Yb, Lu (stockpiled)

Rapidly changing REE markets

- New applications can bring REE market rapidly out of balance
- Presently: market driven by Nd and Dy
- Before 1985:
  - No Nd metal produced in industrial quantities
  - No industrial applications for Dy
- 1980s: market driven by Sm (SmCo magnets)
- 1960s-1970s: market driven by Eu (color TV screens)

- Future: market driven by Gd ? (magnetic refrigeration)

Balance problem: possible solutions

- Diversification of REE resources
- Recycling
- Substitution
- Reduced use
- New high-volume applications

Diversification of REE resources

- Bastnäsite $(Ce,La)(CO_3)F$
- Monazite $(Ce,La,Nd,Th)PO_4$
- Xenotime YPO_4
- Ion-adsorption clays

- Eudialyte $Na_4(Ca,Ce)_2(Fe^{2+},Mn,Y)ZrSi_8O_{22}(OH,Cl)_2$
- Allanite $(Ce,Ca,Y)_2(Al,Fe^{3+})_3(SiO_4)_3OH$
- Loparite $(Ce,La,Na,Ca,Sr)(Ti,Nb)O_3$

- Combining REE ores of different deposits allows making REE concentrate that reflects better market needs of individual REEs

Rare-earth recycling

- *Less than 1%* of the REEs were being recycled in 2011
  inefficient collection, technological issues, lack of incentives
- Main sources:
  - permanent magnets (**Nd**, Pr, Tb, **Dy**)
  - nickel metal hydride batteries (**La**, Ce)
  - lamp phosphors (**Eu**, **Tb**, **Y**, Gd, La, Ce)
- Advantages:
  - no issues with radioactive thorium
  - composition of the obtained REE concentrate is less complex
  - high concentrations, small volumes

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Review

Recycling of rare earths: a critical review

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Substitution

- Replace critical metals by less critical ones
- NdFeB magnets

  Nd → Pr

  Dy → Tb
- SmCo magnets
- Non-REE magnets

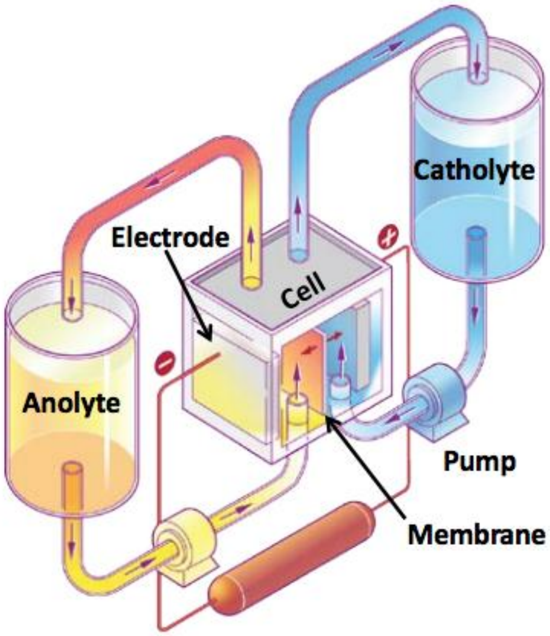
- Fluorescent lamps → LEDs
- CRT → LCD → OLED

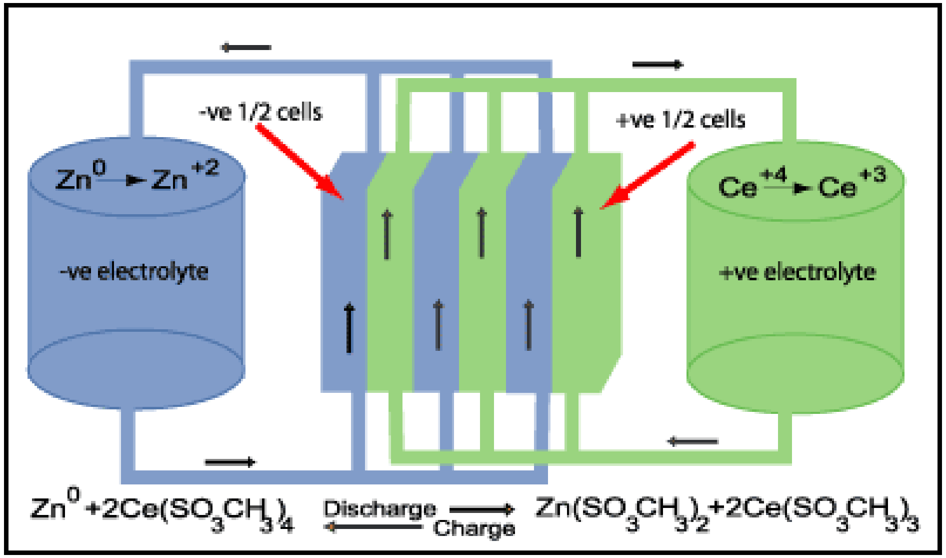
Reduced use

- Less Dy in NdFeB magnets:
  by grain boundary diffusion, Dy is concentrated near grain boundaries
- Removal of Nd from concentrate for making mischmetal

New high-volume applications

- Water purification (phosphate removal): La, Ce
- Cerium in redox flow batteries





Source: Plurion

Conclusions

- Availability of REEs is determined not only by production volumes of REE ores, but also by natural abundances of individual REEs
- Matching supply and demand of all REEs is a challenge (**balance problem**)
- Present market is driven by Nd and Dy demand
- New applications could change market situation rapidly
- Solutions to balance problem

  New REE ores

  Recycling

  Substitution and reduced use

  New high-volume applications (cerium)

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http://www.kuleuven.rare3.eu/

Thank you !

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